PATENT
Case No. DP 305851
(7500/95)

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE
APPLICATION FOR UNITED STATES LETTERS PATENT

INVENTOR(S):   VARDARAJAN R. IYENGAR
BRUCE A. HEASTON
JOHN F. HOYING
DAVID A. SHAL
DARIN D. DELLINGER
KHALED M. JUNDI
JESSE D. JONES
TIMOTHY J. JUUHL
ROBIN OAKLEY
DAVID J. BARTA
MICHAEL R. LUKUC

TITLE: TEMPERATURE COMPENSATION
FOR MAGNETORHEOLOGICAL FLUID
DAMPERS

ATTORNEYS: SCOTT A. MCBAIN, ESQ.
DELPHI TECHNOLOGIES INC.
LEGAL STAFF
P.O. BOX 5052
MAIL CODE: 480-414-420
TROY, MICHIGAN 48007-5052
(248) 267-5514

DP 305851

5   TEMPERATURE COMPENSATION
FOR MAGNETORHEOLOGICAL FLUID DAMPERS

BACKGROUND OF THE INVENTION

10

1.   FIELD OF THE INVENTION

The present invention generally relates to an operation of a magnetorheological fluid (MR) damper. The present invention specifically relates to an application of a temperature compensation to an operating current of a MR

15   damper.

2.   DESCRIPTION OF THE RELATED ART

FIG. 1 illustrates a MR damper 10 as known in the art. MR damper 10 includes a cylindrical tube 11 and a cylindrical sleeve 12 affixed to an outer surface

20   of an upper end of cylindrical tube 11 whereby a cavity is formed. The cavity contains a magnetorheological (MR) fluid consisting of small soft-magnetic particles dispersed throughout the cavity. A cylindrical valve 13 having an annular fluid passageway 14 and a coil 15 is slidably positioned within the cavity. Any linear displacement of valve 13 within the cavity involves some degree of flow of the MR

25   fluid through fluid passageway 14. A rod 16 extends through sleeve 12 and is adjoined to valve 13 whereby valve 13 is linearly displaced within the cavity whenever an operating force in the form of a compression force CF or an extension force EF being applied to rod 16 exceeds a damping force of the MR fluid within the cavity.

30

The damping force of the MR fluid is a combination of laminar forces related to a fluid viscosity of the MR fluid and the dimensions of fluid passageway 14, and shear forces due to the MR effect. Thus, to generate the damping force at a

5 desired force level, a controller 20 supplies an operating current Ios having a corresponding ampere level to a coil 16 via a conductor 21 whereby a magnetic field of a corresponding strength is generated. However, the fluid viscosity of the MR fluid varies strongly with an operating temperature of MR damper 10 based upon an ambient temperature of MR damper 10 and any internal heat generated during an

10 operation of MR damper 10. Consequently, under some operating temperatures, the actual force level of the damping force of the MR fluid can significantly vary from the desired force level of the damping force.

There is therefore a need for a temperature compensation method for overcoming the aforementioned shortcomings described herein. The present

15 invention addresses this need.

SUMMARY OF THE INVENTION

The present invention provides a controller for implementing a method for controlling a damping force of a damper in view of an operating temperature of the

20 damper. Various aspects of the invention are novel, non-obvious, and provide various advantages. While the actual nature of the invention covered herein can only be determined with reference to the claims appended hereto, certain features which are characteristic of the preferred embodiment disclosed herein are described briefly as follows.

25 One form of the present invention is a method for controlling a damping force of a damper. First, a first operating current is determined as a function of a desired force level of the damping force. Second, a temperature compensation as a function of an operating temperature of the damper is determined. Finally, the temperature compensation is applied to the first operating current to generate a

30 second operating current as a function of both the desired force level of the damping force and the operating temperature of the damper.

A second form of the invention is a device for controlling a damping force of a damper. The device includes means for determining a first operating current as a function of a desired force level of the damping force, means for determining a

5   temperature compensation as a function of an operating temperature of the damper, and means for applying the temperature compensation to the first operating current to generate a second operating current as a function of both the desired force level of the damping force and the operating temperature of the damper.

A third form of the invention is a system comprising a damper and a

10   controller. The controller includes means for determining a first operating current as a function of a desired force level of a damping force of the damper, means for determining a temperature compensation as a function of an operating temperature of the damper, and means for applying the temperature compensation to the first operating current to generate a second operating current as a function of both the

15   desired force level of the damping force and the operating temperature of the damper.

The foregoing forms, and other forms, features and advantages of the present invention will become further apparent from the following detailed description of the presently preferred embodiments, read in conjunction with the accompanying

20   drawings. The detailed description and drawings are merely illustrative of the present invention rather than limiting, the scope of the present invention being defined by the appended claims and equivalents thereof.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is an illustration of a MR damper as known in the art;

FIG. 2 is an illustration of a block diagram of a MR damper controller in accordance with the present invention;

FIG. 3A is an illustration of a first exemplary force-velocity curve of the MR damper of FIG. 1;

FIG. 3B is an illustration of a second exemplary force-velocity curve of the MR damper of FIG. 1;

FIG. 3C is an illustration of a third exemplary force-velocity curve of the MR damper of FIG. 1;

FIG. 4 is an illustration of a block diagram of a first embodiment of a temperature detection module in accordance with the present invention;

FIG. 5A is an illustration of a block diagram of a second embodiment of a temperature detection module in accordance with the present invention;

FIG. 5B is an illustration of a flowchart of one embodiment of a estimated damper temperature method in accordance with the present invention;

FIG. 6A is an illustration of a block diagram of a first embodiment of a temperature compensation module in accordance with the present invention;

FIG. 6B is an illustration of a flowchart of a first embodiment of a scale factor determination method in accordance with the present invention;

FIG. 7 is an illustration of a block diagram of a second embodiment of a temperature compensation module in accordance with the present invention;

FIG. 8A is an illustration of a block diagram of one embodiment of a compensation curve determination module in accordance with the present invention;

FIG. 8B is an illustration of a flowchart of one embodiment of a compensation data determination method in accordance with the present invention;

FIG. 9A is an illustration of a block diagram of one embodiment of a compensation parameter determination module in accordance with the present invention;

5   FIG. 9B is an illustration of a flowchart of one embodiment of a scale offset determination method in accordance with the present invention; and

FIG. 9C is an illustration of a flowchart of a second embodiment of a scale factor determination method in accordance with the present invention.

10   DETAILED DESCRIPTION OF THE
PRESENTLY PREFERRED EMBODIMENTS

FIG. 2 illustrates a MR damper controller 30 of the present invention. MR damper controller 30 comprises a conventional current command module 40, a temperature detection module 50, and a temperature compensation module 60. The

15   modules 40, 50, and 60 can include software, hardware in the form of analog and/or digital circuitry, or a combination of software and hardware. In one embodiment, controller 30 includes an integrated processing unit (not shown) operatively coupled to one or more solid-state memory devices (not shown) storing programming corresponding to modules 40, 50 and 60 that is to be executed by the processing

20   unit. The memory devices may be either volatile or nonvolatile and may additionally or alternatively be of the magnetic or optical variety. Besides the memory and processing unit, controller 30 additionally includes any control clocks, interfaces, communication ports, or other types of operators as would occur to those skilled in the art to implement the principals of the present invention.

25   Controller 30 may be employed with any configuration of a MR damper. To facilitate an understanding of the present invention, the following description of modules 40, 50, and 60 herein will be in the context of an employment of controller 30 for controlling MR damper 10 (FIG. 1).

Current command module 40 conventionally provides an operating current
I$_{OS1}$ as a function of a desired force level of the damping force of MR damper 10.
To generate operating current I$_{OS1}$, current command module 40 receives one or

5 more signals 31 as input variables to an algorithm that determines the desired force
level of the damping force of MR damper 10. In one embodiment, MR damper 10
is coupled between a vehicle body and a wheel, and the operating condition signals
31 are indicative of various operating conditions of the vehicle (e.g., vehicle speed,
driver steering and throttle inputs, vehicle body and/or wheel motions and other

10 signals as would occur to those having ordinary skill in the art. In response thereto,
current command module 40 executes one or more conventional algorithms for
determining the desired force level of the damping force of MR damper 10 that
facilitates an optimal ride and handling of the vehicle under a baseline operating
temperature. Such algorithms can include a conventional algorithm for controlling

15 the motion of the vehicle body, a conventional algorithm for controlling the motion
of the wheel, a conventional algorithm for controlling a stability and a handling of
the vehicle, one or more conventional algorithms for managing damper travel
limitations, and other conventional algorithms as would occur to those having
ordinary skill in the art.

20   The result of the execution of the algorithm(s) by current command module
40 is a generation of operating current I$_{OS1}$ at an ampere level to achieve the desired
force level of the damping force as a function of a damping velocity of MR damper
10. For example, FIG. 3A illustrates an exemplary force-velocity calibration curve
of MR damper 10 for an operating temperature of +20°C as the baseline

25 temperature. As shown in FIG. 3A, the ampere level of operating current I$_{OS1}$ must
be 4 amps in order to achieve a desired force level DFL when the damping velocity
of MR damper 10 is 1.00 m/s. The generation of operating current I$_{OS1}$ by current
command module 40 however does not account for the operating temperature of MR
damper 10 being less than or greater than the baseline temperature. Consequently,

30 the desired force level DFL of the damping force may not be achieved. For
example, FIG. 3B illustrates an exemplary force-velocity calibration curve of MR

damper 10 for an operating temperature of -20°C. As shown in FIG. 3B, an actual

force level AFL_1 being greater than the desired force level DFL is achieved when

the ampere level of operating current I_{OS1} is 4 amps and the damping velocity of MR

5   damper 10 is 1.00 m/s under an operating temperature of -20°C. Also by example,

FIG. 3C illustrates an exemplary force-velocity calibration curve of MR damper 10

for an operating temperature of +60°C. As shown in FIG. 3C, an actual force

level AFL_2 being less than the desired force level DFL is achieved when the ampere

level of operating current I_{OS1} is 4 amps and the damping velocity of MR damper 10

10   is 1.00 m/s under an operating temperature of +60°C.

        Temperature detection module 50 and temperature compensation module 60

are collectively directed to an achievement of the desired force level DFL within a

wide range of operating temperatures of MR damper 10. Specifically, temperature

detection module 50 and temperature compensation module 60 operate to determine

15   and apply a temperature compensation to operating current I_{OS1} to generate an

operating current I_{OS2} as a function of both the desired force level of the damping

force of MR damper 10 and the operating temperature of MR damper 10. For

example, referring to FIG. 3B, operating current I_{OS2} would be generated with an

ampere level approximating 3.5 amps when the damping velocity of MR damper 10

20   is 1.00 m/s under an operating temperature of -20°C to thereby substantially achieve

the desired force level DFL. Also by example, referring to FIG. 3C, operating

current I_{OS2} would be generated with an ampere level approximating 4.2 amps when

the damping velocity of MR damper 10 is 1.00 m/s under an operating temperature

of +60°C to thereby substantially achieve the desired force level DFL.

25   Individual descriptions of various embodiments of temperature detection

module 50 and temperature compensation module 60 will now be described herein.

Temperature detection module 50 provides an operating temperature signal OTs2 in response to a reception of either an operating temperature signal OTs1 that is indicative of a directly or indirectly measured operating temperature of MR damper

5   10. FIG. 4 illustrates a temperature detection module 150 as one embodiment of temperature detection module 50. Temperature detection model 150 includes a conditioning circuit 151 for receiving operating temperature signal OTs1 (FIG. 2) in the form of an ambient temperature signal ATs1 that is indicative of an ambient temperature of MR damper 10 (i.e., temperature of the air surrounding MR damper

10   10 or a system incorporating MR damper 10, such as, for example, a vehicle). When MR damper 10 is employed within a vehicle, ambient temperature signal ATs1 can be provided by an outside air temperature sensor, an engine air intake sensor, and other sensors as would occur to those having ordinary skill in the art. In response to a reception of ambient temperature signal ATs1, conditioning circuit 151

15   conditions ambient temperature signal ATs1 to provide an ambient temperature signal ATs2 serving as operating temperature signal OTs2 (FIG. 2). Such conditioning can include analog-to-digital conversion, signal scaling or conversion operations, analog or digital filtering operations, and other conditioning techniques as would occur to those having ordinary skill in the art. Alternatively, conditioning circuit 151 can

20   receive operating temperature signal OTs1 in the form of a damper temperature signal DTs1 that is indicative of the internal temperature of MR damper 10 as directly measured within the cavity of MR damper 10 via a thermocouple or the like. In response to a reception of damper temperature signal DTs1, conditioning circuit 151 conditions damper temperature signal DTs1 to provide a damper

25   temperature signal DTs2 serving as operating temperature signal OTs2.

FIG. 5A illustrates a temperature detection module 250 as a second embodiment of temperature detection module 50. Temperature detection model 250 includes a damper temperature estimation module 251 for receiving operating

5   temperature signal OT_{SI} (FIG. 2) in the form of ambient temperature signal AT_{SI} and a plurality of signals 252 indicative of various operating conditions of MR damper 10 (e.g., a damper force/current and a damper velocity). In response to a reception of ambient temperature signal AT_{SI} and signals 252, damper temperature estimation module 251 provides an estimated damper temperature signal ET_S as a computation

10   of an execution of a thermal energy model method of the present invention.

FIG. 5B illustrates a flowchart 350 as a representation of the thermal model method. Damper temperature estimation module 251 determines a current thermal energy state of MR damper 10 during stage S352 of flowchart 350. In one embodiment, damper temperature estimation module 251 determines an initial energy

15   consumption by MR damper 10 during an initial operation of MR damper 10 to thereby establish an initial thermal energy state of MR damper 10. Thereafter, damper temperature estimation module 251 downwardly adjusts the initial thermal energy state of MR damper 10 in view of various cooling effects upon MR damper 10 between operations of MR damper 10 and upwardly adjusts the thermal energy

20   state in view of additional energy consumption by MR damper 10 during subsequent operations of the MR damper 10. Those having ordinary skill in the art will appreciate various ways for determining energy consumption of MR damper 10 during operations of MR damper 10 and various cooling effects upon MR damper 10 between operations of MR damper 10 as well as the required signals 252.

25

The current thermal energy state is therefore the current summation of the total energy consumption by MR damper 10 and the total cooling effects upon MR damper 10 as of the instance damper temperature estimation module 251 implements

5   stage S352. During a stage S354 of flowchart 350, damper temperature estimation module 251 determines a delta temperature T corresponding to the current thermal energy state of MR damper 10. In one embodiment, experimental data correlating delta temperatures to thermal energy states of MR damper 10 can be generated and stored whereby the experimental data can serve as a basis for a computation or

10   retrieval of delta temperature T corresponding to the current thermal energy state of MR damper 10.

During a stage S356 of flowchart 350, damper estimation temperature module 251 generates estimated temperature signal ET_s as a summation of ambient temperature signal AT_{s1} and delta temperature T. The execution of flowchart 350

15   by damper temperature estimation module 251 can be discontinuous as shown, or continuous as indicated by the dashed arrow.

Referring again to FIG. 2, an alternative embodiment of temperature damper controller 30 can omit temperature detection module 50 whereby operating temperature signal OT_{s1} in the form of ambient temperature signal AT_{s1} (FIG. 4) or

20   damper temperature signal DT_{s1} (FIG. 4) is directly provided to temperature compensation module 60.

Temperature compensation module 60 provides operating current I_{os2} in response to a reception of operating current I_{os1} and operating temperature signal OT_{s2} (or alternatively operating temperature signal OT_{s1}). Operating current I_{os2} is

25   a function of the desired force level of the damping force of MR damper 10 as indicated by operating current I_{os1} and the operating temperature of MR damper 10 as indicated by operating temperature signal OT_{s2} (or alternatively operating temperature signal OT_{s1}).

FIG. 6A illustrates a temperature compensation module 160 as one embodiment of temperature compensation module 60. Temperature compensation module 160 includes scale factor module 161 having data representative of a scale

5   factor curve 162 for providing a scale factor signal SF_{s1} in response to a reception of operating temperature signal OT_{s2} (or alternatively operating temperature signal OT_{s1}). In generating scale factor signal SF_{s1}, scale factor module 161 implements a scale factor determination method in accordance with the present invention that is based upon operating temperature signal OT_{s2} (or alternatively operating

10   temperature signal OT_{s1}). FIG. 6B illustrates a flowchart 260 that is representative of the scale factor determination method.

During a stage S262 of flowchart 260, scale factor module 161 determines if operating temperature signal OT_{s2} (or alternatively operating temperature signal OT_{s1}) is less than a temperature T1 (e.g., -20 C) as listed in scale factor curve 162.

15   If so, during a stage S264 of flowchart 260, scale factor module 161 generates scale factor signal SF_{s1} equating scale factor SF1 as listed in scale factor curve 162.

Otherwise, during a stage S266 of flowchart 260, scale factor module 161 determines if operating temperature signal OT_{s2} (or alternatively operating temperature signal OT_{s1}) is less than a temperature T2 (e.g., 0 C) as listed in scale

20   factor curve 162. If so, during a stage S268 of flowchart 260, scale factor module 161 generates scale factor signal SF_{s1} equating a computation of an interpolation equation illustrated in stage S268, which is a function of scale factor SF1, a scale factor SF2, temperature T1, and temperature T2 as listed in scale factor curve 162.

Otherwise, during a stage S270 of flowchart 260, scale factor module 161

25   determines if operating temperature signal OT_{s2} (or alternatively operating temperature signal OT_{s1}) is less than a temperature T3 (e.g., +20 C) as listed in scale factor curve 162. If so, during stage S272 of flowchart 260, scale factor module 161 generates scale factor signal SF_{s1} equating a computation of an interpolation equation illustrated in stage S272, which is a function of scale factor

30   SF2, a scale factor SF3, temperature T2, and temperature T3 as listed in scale factor curve 162.

Otherwise, during a stage S274 of flowchart 260, scale factor module 161 determines if operating temperature signal OT_{S2} (or alternatively operating temperature signal OT_{S1}) is less than a temperature T4 (e.g., +35 C) as listed in

5   scale factor curve 162. If so, during stage S276 of flowchart 260, scale factor module 161 generates scale factor signal SF_{S1} equating a computation of an interpolation equation illustrated in stage S276, which is a function of scale factor SF3, a scale factor SF4, temperature T3, and temperature T4 as listed in scale factor curve 162.

10   Otherwise, during a stage S278 of flowchart 260, scale factor module 161 determines if operating temperature signal OT_{S2} (or alternatively operating temperature signal OT_{S1}) is less than a temperature T5 (e.g., +60 C) as listed in scale factor curve 162. If so, during stage S280 of flowchart 260, scale factor module 161 generates scale factor signal SF_{S1} equating a computation of an

15   interpolation equation illustrated in stage S280, which is a function of scale factor SF4, a scale factor SF5, temperature T4, and temperature T5 as listed in scale factor curve 162. Otherwise, during a stage S282 of flowchart 260, scale factor module 161 generates scale factor signal SF_{S1} equating scale factor SF5 as listed in scale factor curve 162.

20   Referring again to FIG. 6A, temperature compensation module 160 further includes a multiplier 163 for providing operating current signal I_{OS2} as a product of operating current signal I_{OS1} and scale factor signal SF_{S1}. MR damper 10 has a defined operating current range (e.g., 0 to 5 amperes) relating to the associated design of coil 15 (FIG. 1) and a desired range of the damping force. Accordingly,

25   operating current signal I_{OS2}, having been computed as the product of operating current I_{OS1} and scale factor signal SF_{S1} is then compared against the pre-defined upper and lower operating currents of the MR damper 10. If I_{OS2} is less than a lower operating limit (e.g., 0 amps), I_{OS2} is set equal to the lower operating limit. Otherwise, if I_{OS2} is greater than an upper operating limit (e.g., 5 amps), I_{OS2} is set

30   equal to the upper operating limit. The need for these steps would be appreciated by those having ordinary skill in the art.

FIG. 7 illustrates a temperature compensation module 360 as one embodiment of temperature compensation module 60. Temperature compensation module 360 includes a compensation curve determination module 370 for providing scale factor data 371 ("SFD 371") having computed scale factors SF1-SF5 and offset data 372 ("OSD 372") having computed offset values OV1-OV5 in response to a reception of operating temperature signal OT_{s2} (or alternatively operating temperature signal OT_{s1}). One embodiment of a compensation data method for computing the scale factors SF1-SF5 included within SFD 371 and computing the offset values OV1-OV5 includes within OSD 372 will be subsequently described herein in connection with FIG. 8B.

Referring still to FIG. 7, temperature compensation module 360 further includes a compensation parameter determination module 380 for providing a scale factor signal SF_{s2} and an offset value signal OV_s in response to a reception of SFD 371, OSD 372, and a relative velocity signal RV_s that is indicative of a velocity of MR damper 10 relative to one or more fixed point(s). When MR damper 10 is employed in a vehicle, the fixed points are represented by a coupling of MR damper 10 to a vehicle body and a coupling of MR damper 10 to a wheel whereby relative velocity signal RV_s is indicative of a velocity of MR damper 10 in response to the relative motions of the vehicle and the wheel. Temperature compensation module 360 further includes a multiplier 390 for providing an operating current I_{os3} as a product of scale factor signal SF_{s2} and operating current I_{os1} (FIG. 2) and an adder 391 for providing operating current I_{os2} (FIG. 2) as a summation of offset value signal OV_s and operating current I_{os3}. In an alternative embodiment of temperature compensation module 360, adder 391 provides operating current I_{os3} as a summation of operating current I_{os1} and offset value signal OV_s, and multiplier 390 provides operating current I_{os2} as a product of scale factor signal SF_{s2} and operating current I_{os3}.

Again, MR damper 10 has a defined operating current range (e.g., 0 to 5 amperes) relating to the associated design of coil 15 (FIG. 1) and a desired range of the damping force. Accordingly, operating current signal I_{OS2}, having been

5 computed as the sum of operating current I_{OS3} and scale factor signal OV_S is then compared against the pre-defined upper and lower operating currents of MR damper 10. If I_{OS2} is less than a lower operating limit (e.g., 0 amps), I_{OS2} is set equal to the lower operating limit. Otherwise, if I_{OS2} is greater than an upper operating limit (e.g., 5 amps), I_{OS2} is set equal to the upper operating limit. The need for these

10 steps would be obvious to those having ordinary skill in the art.

FIG. 8A illustrates a compensation curve determination module 470 as one embodiment of compensation curve determination module 370 (FIG. 7). Compensation curve determination module 470 provides SFD 371 (FIG. 7) and OSD 372 (FIG. 7) in response to a reception of operating temperature signal OT_{S2}

15 (or alternatively operating temperature signal OT_{S1}). In generating SFD 371 and OSD 372, compensation curve determination module 470 includes data representative of a scale factor curve 471a ("SFC 471a"), a scale factor curve 471b ("SFC 471b"), a scale factor curve 471c ("SFC 471c"), an offset curve 471a ("OSC 472a"), an offset curve 471b ("OSC 472b"), and an offset curve 471c ("OSC

20 472c"). The scale factors SF1-SF5 of scale factor curves 471a-471c are dissimilar due to a correlation of scale factor curves 471a-471c to three (3) different operating temperatures of MR damper 10 (e.g., -20 C, +20 C, and +60 C), respectively. The offset values OV1-OV5 of offset curves 472a-472c are dissimilar due to a correlation of offset curves 472a-472c to three (3) different operating temperatures

25 of MR damper 10 (e.g., -20 C, +20 C, and +60 C), respectively. The relative velocities RV1-RV5 of both scale factor curves 471a-471c and offset curves 472a-472c are identical. Compensation curve determination module 470 utilizes one or more of the scale factor curves 471a-471c and offset curves 472a-472c in implementing a compensation data determination method in accordance with the

30 present invention. FIG. 8B illustrates a flowchart 570 that is representative of the compensation data determination method.

During a stage S572 of flowchart 570, compensation curve determination module 470 determines if operating temperature signal OT_{S2} (or alternatively operating temperature signal OT_{S1}) is less than a temperature T6 (e.g., -20 C). If

5 so, during a stage S574 of flowchart 570, compensation curve determination module 470 generates the scale factors SF1-SF5 of SFD 371 as equating the scale factors SF1-SF5 of SFC 471a, respectively. Compensation curve determination module 470 also generates the offset values OV1-OV5 of OSD 372 as equating the offset values OV1-OV5 of OSC 472a.

10 Otherwise, during a stage S576 of flowchart 570, compensation curve determination module 470 determines if operating temperature signal OT_{S2} (or alternatively operating temperature signal OT_{S1}) is less than a temperature T7 (e.g., +20 C). If so, during a stage S578 of flowchart 570, compensation curve determination module 470 generates the scale factors SF1-SF5 of SFD 371 as

15 equating a computation of an interpolation equation illustrated in stage S578 which is a function of both the scale factors SF1-SF5 of SFC 471a and the scale factors of SFC 471b. Compensation curve determination module 470 also generates the offset values OV1-OV5 of OSD 372 as equating a computation of an interpolation equation illustrated in stage S578 which is a function of both the offset values OV1-OV5 of

20 OSC 472a and the scale factors of OSC 472b.

Otherwise, during a stage S580 of flowchart 570, compensation curve determination module 470 determines if operating temperature signal OT_{S2} (or alternatively operating temperature signal OT_{S1}) is less than a temperature T8 (e.g., +60 C) as listed in SFCs 471a-471c and OSCs 472a-472c. If so, during a stage

25 S582 of flowchart 570, compensation curve determination module 470 generates the scale factors SF1-SF5 of SFD 371 as equating a computation of an interpolation equation illustrated in stage S582 which is a function of both the scale factors SF1-SF5 of SFC 471b and the scale factors of SFC 471c. Compensation curve determination module 470 also generates the offset values OV1-OV5 of OSD 372 as

30 equating a computation of an interpolation equation illustrated in stage S582 which is a function of both the offset values OV1-OV5 of OSC 472b and the scale factors of OSC 472c.

Otherwise, during a stage S584 of flowchart 260, compensation curve determination module 470 the scale factors SF1-SF5 of SFD 371 as equating the scale factors SF1-SF5 of SFC 471c, respectively. Compensation curve

5   determination module 470 also generates the offset values OV1-OV5 of OSD 372 as equating the offset values OV1-OV5 of OSC 472c.

FIG. 9A illustrates a compensation parameter determination module 480 as one embodiment of compensation parameter determination module 380 (FIG. 7). Compensation parameter determination module 480 provides scale factor signal SFs2

10   (FIG. 7) and offset value signal OVs (FIG. 7) in response to relative velocity signal RVs, SFD 371, and OSD 372. In generating scale factor signal SFs2, compensation parameter determination module 480 includes a scale factor curve 481 ("SFC 481") that includes scale factor data SF1-SF5 included within SFD 371, and relative velocities RV1-RV5 that are identical to the relative velocities RV1-RV5 listed in

15   SFC 471a-471c and OSC 472a-472c (FIG. 8A). Compensation parameter determination module 480 utilizes SFC 481 in implementing a scale factor determination method in accordance with the present invention. FIG. 9B illustrates a flowchart 680 that is representative of the scale factor determination method.

During a stage S682 of flowchart 680, compensation parameter

20   determination module 480 determines if relative velocity signal RVs is less than a relative velocity RV1 as listed in SFC 481. If so, during a stage S684 of flowchart 680, compensation parameter determination module 480 generates scale factor signal SFs2 equating a scale factor SF1 as listed in SFC 481.

Otherwise, during a stage S686 of flowchart 680, compensation parameter

25   determination module 480 determines if relative velocity signal RVs is less than a relative velocity RV2 as listed in SFC 481. If so, during a stage S688 of flowchart 680, compensation parameter determination module 480 generates scale factor signal SFs2 equating a computation of an interpolation equation illustrated in stage S688, which is a function of scale factor SF1, a scale factor SF2, relative velocity

30   RV1, and relative velocity RVs as listed in SFC 481.

Otherwise, during a stage S690 of flowchart 680, compensation parameter determination module 480 determines if relative velocity signal RVs is less than a relative velocity RV3 as listed in SFC 481. If so, during a stage S692 of flowchart

5   680, compensation parameter determination module 480 generates scale factor signal SFs2 equating a computation of an interpolation equation illustrated in stage S692, which is a function of scale factor SF2, a scale factor SF3, relative velocity RV2, and relative velocity RV3 as listed in SFC 481.

Otherwise, during a stage S694 of flowchart 680, compensation parameter

10   determination module 480 determines if relative velocity signal RVs is less than a relative velocity RV4 as listed in SFC 481. If so, during a stage S696 of flowchart 680, compensation parameter determination module 480 generates scale factor signal SFs2 equating a computation of an interpolation equation illustrated in stage S696, which is a function of scale factor SF3, a scale factor SF4, relative velocity

15   RV3, and relative velocity RV4 as listed in SFC 481.

Otherwise, during a stage S698 of flowchart 680, compensation parameter determination module 480 determines if relative velocity signal RVs is less than a relative velocity RV5 as listed in SFC 481. If so, during a stage S700 of flowchart 680, compensation parameter determination module 480 generates scale factor

20   signal SFs2 equating a computation of an interpolation equation illustrated in stage S700, which is a function of scale factor SF4, a scale factor SF5, relative velocity RV4, and relative velocity RV5 as listed in SFC 481.

Otherwise, during a stage S702 of flowchart 680, compensation parameter determination module 480 generates scale factor signal SFs2 equating scale factor

25   SF5 as listed in SFC 481.

In generating offset value signal OVs, compensation parameter determination module 480 includes an offset curve 482 ("OSC 482") that includes offset values OV1-OV5 included within OSD 372, and relative velocities RV1-RV5 that are

5   identical to the relative velocities RV1-RV5 listed in SFC 471a-471c and OSC 472a-472c (FIG. 8A). Compensation parameter determination module 480 utilizes OSC 482 in implementing an offset value determination method in accordance with the present invention. FIG. 9C illustrates a flowchart 780 that is representative of the offset value determination method.

10   During a stage S782 of flowchart 780, compensation parameter determination module 480 determines if relative velocity signal RVs is less than a relative velocity RV1 as listed in OSC 482. If so, during a stage S784 of flowchart 780, compensation parameter determination module 480 generates offset value signal OVs equating an offset value OV1 as listed in OSC 482.

15   Otherwise, during a stage S786 of flowchart 780, compensation parameter determination module 480 determines if relative velocity signal RVs is less than a relative velocity RV2 as listed in OSC 482. If so, during a stage S788 of flowchart 780, compensation parameter determination module 480 generates offset value signal OVs equating a computation of an interpolation equation illustrated in stage

20   S788, which is a function of offset value OV1, an offset value OV2, relative velocity RV1, and relative velocity RVS as listed in OSC 482.

Otherwise, during a stage S790 of flowchart 780, compensation parameter determination module 480 determines if relative velocity signal RVs is less than a relative velocity RV3 as listed in OSC 482. If so, during a stage S792 of flowchart

25   780, compensation parameter determination module 480 generates offset value signal OVs equating a computation of an interpolation equation illustrated in stage S792, which is a function of offset value OV2, an offset value OV3, relative velocity RV2 and relative velocity RV3 as listed in OSC 482.

Otherwise, during a stage S794 of flowchart 780, compensation parameter determination module 480 determines if relative velocity signal RVs is less than a relative velocity RV4 as listed in OSC 482. If so, during a stage S796 of flowchart 780, compensation parameter determination module 480 generates offset value signal OVs equating a computation of an interpolation equation illustrated in stage S796, which is a function of offset value OV3, an offset value OV4, relative velocity RV3, and relative velocity RV4 as listed in OSC 482.

Otherwise, during a stage S798 of flowchart 780, compensation parameter determination module 480 determines if relative velocity signal RVs is less than a relative velocity RV5 as listed in OSC 482. If so, during a stage S800 of flowchart 780, compensation parameter determination module 480 generates offset value signal OVs equating a computation of an interpolation equation illustrated in stage S800, which is a function of offset value OV4, an offset value OV5, relative velocity RV4 and relative velocity RV5 as listed in OSC 482.

Otherwise, during a stage S802 of flowchart 780, compensation parameter determination module 480 generates offset value signal OVs equating offset value OV5 as listed in OSC 482.

Referring to FIGS. 6B, 8B, 9B and 9C, those having ordinary skill in the art will appreciate that the sets of operations depicted in flowcharts 260, 570, 680 and 780, respectively, each represents one of many possible methods for implementing a mathematical relationship between the associated input and output parameters. In the illustrated embodiments, flowcharts 260, 570, 680 and 780 each depict table look-up operations with a plurality of points, with interpolation used between points and saturation used at the extremes. In alternative embodiments of flowcharts 260, 570, 680 and 780, the look-up table operations may include extrapolation beyond the look-up table end-points in lieu of saturation and/or direct selection of look-up table points between table points in lieu of linear interpolation. Furthermore, the number of points illustrated in the look-up tables of FIGS. 6A, 8A and 9A can be increased or decreased based on the desired look-up table resolution and any existing implementation limitations (e.g., size of computer memory). In addition to

the look-up table embodiments described herein, many other alternative embodiments also exist, such as, for example, implementation of a polynomial equation relating the output parameter to the input parameter.

5   Those having ordinary skill in the art will appreciate various advantages of the present invention for the preceding description herein of FIGS. 2-9C. One important advantage is a nearly ideal temperature compensation within the limits of a damper performance envelope of MR damper 10 (FIG. 1). Specifically, current command module 40 (FIG. 2) generates operating current I_{os1} (FIG. 2) which has a

10   known correlation to a damping force of MR damper 10 at a measured velocity of MR damper 10, and a baseline temperature. The various temperature- and relative velocity-dependent offset and scale factor curves described in connection with FIGS. 6A, 8A, and 9A are accordingly developed to optimize a temperature compensation to generate operating current I_{os2} (FIG. 2) that allows MR damper 10 to produce the

15   damping force at a_measured velocity in view of the existing operating temperature of MR damper 10.

      The present invention has been described herein in the context of controlling a MR damper. The present invention, however, can be employed to control other controllable dampers as would occur to those having ordinary skill in the art, such

20   as, for example, controllable dampers using one or more electro-mechanical valve(s). Additionally, the present invention can be employed in other devices using MR fluid or the like as would occur to those having ordinary skill in the art, such as, for example, fan clutches and engine mounts.

      While the embodiments of the present invention disclosed herein are

25   presently considered to be preferred, various changes and modifications can be made without departing from the spirit and scope of the invention. The scope of the invention is indicated in the appended claims, and all changes that come within the meaning and range of equivalents are intended to be embraced therein.